Making a Fast Pulse Induction Mono Coil

A Practical How-to Guide and Tutorial

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Introduction

This article explains and shows you how to make a fast mono coil for a pulse induction (PI) metal detector. The word "fast" refers to the ability of the coil to operate at low sampling delays. Unfortunately, there is not just one thing you can do to make a fast coil, but there are a few things you can do that collectively contribute to the coil's performance on your PI machine.

A little theory is needed to appreciate the design process necessary to make a fast coil. The value of the damping resistor reveals the total coil and TX circuit capacitance that must be critically damped. Higher values of the damping resistor cause higher current dissipation. This also causes faster current decays due to less capacitance. The damping resistor value along with the front-end amplifier input resistor (R12 on the Hammerhead) plus the two clamping diodes also helps to control coil's bandwidth and also controls the peak fly-back voltage generated by the coil. This article describes practical ways to minimize coil and TX circuit capacitance necessary to make a fast, wide bandwidth coil.

The mono coil functions as both the transmit (TX) and receive (RX) coil and is the easiest coil to make. The practical aspects of coil making will be emphasized, leaving the more detailed theory to be found in the references section. As the coil described in this article is being made, critical coil measurements are documented and shared with the readers to demonstrate the concepts being explained. To my knowledge, this detailed approach to coil making has not been documented before. Those seeking to understand the more subtle aspects of PI coil making will appreciate this approach.

PI mono coils can be almost any shape and diameter but some practical design considerations are:

- Desired delay
- Coil resistance
- Inductance necessary to match the PI circuit design requirements
- Size, composition and depth of objects sought
- Diameter of the selected coil housing
- Weight of the finished coil
- Shielding technique used
- Coaxial cable length.

The focus of this article will be on making a round coil but the techniques described can be used to make any shape and size coil. If you are using a coil housing that is non-circular, convert its shape to an equivalent circle and re-shape the finished round coil to fit the coil housing.

This how-to guide will demonstrate the making of a fast coil for the Hammerhead Pulse Induction metal detector that can be used to locate coin-size objects, gold jewelry and gold nuggets. Coil data will be presented along with a comparison to alternate construction methods. This method will form the basis of a tutorial about the techniques used to make this coil as well help you understand the consequences of using coil parts you might have on hand.

A fast coil will operate at low pulse delay settings between 8 to 10 microseconds (us). These low pulse delays are typically used for detecting small gold objects as their signal decays quickly. For those who primarily seek coins or other larger objects that use longer delays in the 30us to 50us range, these coil-making tips will help also. Coils for longer delays do not need a shield and typically operate at lower pulse frequencies (100 to 400 pulses per second) with higher peak current pulses due to the use of thicker coil wire which has a lower resistance. This thicker coil wire, AWG 22 to 26, should be the stranded type to minimize eddy currents being generated in the coil itself. At longer delays, any type of wire insulation can be used. Unshielded coils still need the spiral wrap (3/16 to ¼" ID) or other method, such as electrical tape or lacing to secure the coil windings. If you are using a longer delay coil in an area with high electrical noise, it is better to shield the coil to help make it run quieter. At these longer delays, the coil shield will have a minimal impact on coil sensitivity even though the shield might be detected at lower delays on a different PI machine operating at a lower delay.

All coils have three primary characteristics: inductance (uH), capacitance (pF) and resistance (Ohms). These characteristics can be adjusted individually but interact to impact the final coil performance. The parameters that will affect your coil's ultimate performance are:

- Coil housing diameter
- Wire size (AWG or SWG)
- Wire insulation thickness
- Wire insulation material
- Shield spacer material
- Shield spacer thickness
- Coax cable type and length

- MOSFET COSS output capacitance
- Coil inductance (diameter and number of coil turns) to match the PI circuit design requirements.

Each of these characteristics will be examined in detail and measured (where possible) as it relates to building a coil.

Designing A Mono Coil

Let's start the mono coil design process. The first consideration is the coil housing size that will be used. This coil housing size will define your coil diameter. Commercial-looking coil housings can be obtained through www.hayselectronics.com. Home-made housings can be made by the creative use of common items such as a Frisbee, plastic plate, plastic can lid or anything round that is not metallic. The outside diameter (OD) of the wire used for the coil will determine the thickness of the coil bundle and affect the calculated coil inductance.

If you choose to make a coil for delays below about 30us, a shield must be used to prevent the ground from being detected when the coil is lowered. The shield spacer and shield thickness add to the wire bundle cross-section diameter. I must repeat: the total cross-section of the wire bundle, including all spacers, must be subtracted from the maximum coil diameter that fits your housing; otherwise you will be winding another slightly smaller coil. Before you make your coil form, you need to know the accurate inside diameter (ID) of the coil winding. This measurement will define the coil form diameter and ultimately determine the final fit of your coil inside the coil housing.

If you want to be a little creative, you can use something like a plastic paint can or bucket lid as a coil housing. You must do accurate measurements and calculations to make sure that the finished coil fits inside the lid groove. Wind one-turn inside the lid groove and secure the ends together so you can place the same one turn loop snugly on the coil form (explained later). Make this wire length 6.28 times longer than the combined wall thickness of the shield and spacer material. Adding this little extra length to the coil circumference ensures a good fit inside the lid groove. This extra length accommodates the increase in coil ID from adding the coil spacer and shield. There is not much room for error but with careful planning and measuring, it can be done.

I am going to use AWG 30 single strand Teflon wire that is 0.024"OD (+/- .002"). I obtained my Teflon wire from eBay (search on the words "Teflon wire"). If you are using different wire, just substitute your measured wire OD and follow along with the design process. You need to accurately measure the OD of your wire with a gauge. For a 300 to 350uH coil with 18 to 20 turns, multiply the wire OD by 5 to closely approximate the OD of the wire bundle. This wire bundle will be 0.12" or about 1/8". When calculating your coil size and inductance, go to the following on-line coil inductance calculator. http://my.athenet.net/~multiplx/cgi-bin/airind.main.cgi.

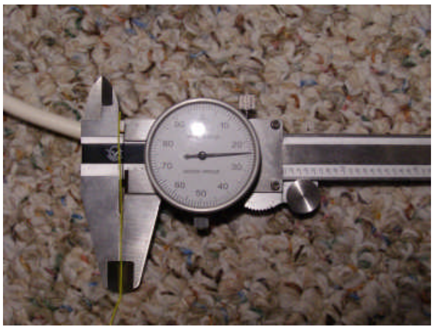

Fig. 1 Measuring OD of AWG 30 Teflon wire.

Use the ID of the coil as the coil diameter input and the wire bundle size as the coil length input and enter the number of turns to calculate the coil's inductance. Use the 1% answer on the above on-line calculator and your calculated inductance will be very close to the actual coil inductance. If you are making a coil with 25 to 27 turns, multiply the wire diameter by 6 and if it is 34 to 37 turns, use 7 as the multiplier to approximate the wire bundle diameter. Go to the following web link to see the complete chart for accurately calculating coil bundle sizes from 1 to 61 turns: http://www.raychem.com/fetch.asp?fileid=980&docId=846

Accurately making the following measurements and calculations ensures that your finished coil fits your coil housing. For a shield spacer, I will use 1/16"ID/1/8"OD polyethylene spiral wrap obtained from www.usplastic.com.

When the spiral wrap is added to the wire bundle, the bundle diameter will increase about 1/16" more. If you want to make a coil with minimal coil-to-shield capacitance, use two layers of spiral wrap, one 1/8" OD diameter and the other 0.250" OD. Subtract 1.5 times the total wire bundle diameter including all layers of spiral wrap plus shield added to the coil from the maximum coil housing diameter to obtain the actual winding ID of your coil form. The reason I use 1.5 and not 2 is that there are two thicknesses of the spiral wrap on each side, making up a total of 4 thicknesses. The two layers on the inside of the coil and do not increase the OD fit of the coil. The final coil bundle cross-section diameter with the Scotch 24 shield and final tape wrap is .315" and just fits the 11" Hayes Electronics coil housing with little room to spare.

Fig. 2 Measuring the diameter of final shielded coil bundle.

Making A Coil Form

Here is a quick and accurate way to make a coil form that allows you to make any size coil. Obtain 17 "C" type screw-in hooks (also known as cup hooks). Place two hooks on a flat surface with the opening of the hooks facing left and right and the threaded shafts parallel. Accurately space and measure the inside distance between the

Fig. 3 Cup hooks used for my coil.

hooks, where the wire will lay, to be exactly the same as the inside diameter (ID) of your new coil. Now, measure the distance between the points of the two screw tips of the "C" hooks. This will be the diameter of the circle you will make with a compass on a piece of plywood.

Equally divide up the circle so you can place 16 "C" hooks on this circle. Make sure the "C" hooks go in straight so the actual ID of your coil will be accurate. If you use the tall "C" hooks, you can bend opposite "C" hooks slightly to make small adjustments to the coil inside diameter. Place a mark around one hook that will become the coil start and end point as well as the coil turn counting point of reference.

Before winding your coil, you should check the accurate ID of your "C" hook coil form by wrapping one loop of wire around all the hooks. Pull the wire tight as it goes over one hook and then place a mark on the wires. Measure the distance between the marks on this piece of wire and divide this length by 3.14159 and you will confirm the actual diameter of your coil. Adjust if necessary.

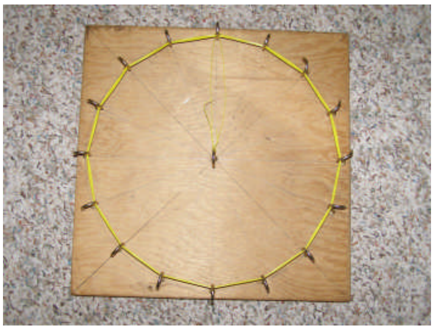

Fig. 4 Cup hooks mounted to make coil form.

Place another hook in the coil center to hold the start and end windings. Place the start of your winding on the center "C" hook and wind the calculated number of turns around the 16 "C" hooks. ***Important: secure the winding on this center hook with a few turns of electrical tape to ensure that the windings don't come loose so tension is maintained when later adding the spiral wrap spacer.***

My coil uses 19 turns of AWG 30. Place the end winding on the center "C" hook, secure with tape and cut the wire. Inspect the winding to ensure that the coil windings are snug and not snagged on anything.

Applying The Shield Spacer

With the coil wire still on the "C" hooks, you can apply the spiral wrap without the need to lace it. This is the main reason to use the "C" hook coil form. If you measure the inductance of the coil on the "C" hooks, 19 turns of AWG 30 on a 10.5" ID gives you about 285uH. Once the spiral wrap is added, the wire bundle is held tighter and the inductance is about 317uH. Since the ID of the spiral wrap is 1/16" it will expand to accommodate the 0.12" 19-turn wire bundle (.024" X 5= .12"). Cut the 1/8" OD spiral wrap 1.65 times the coil circumference (not stretched) to accommodate this expansion with a few inches to spare. Starting at the location of the two coil leads, begin applying the spiral wrap. You can actually slip the spiral wrap under the hooks where the wire crosses each hook.

Fig. 5 Close-up of spiral wrap. See how spiral wrap can be easily slipped under each hook.

Continue wrapping around the total coil and only remove the coil from the "16 "C" hooks when you are close to finishing the spiral wrap. Turn a few "C" hooks 90 degrees and carefully slip off the spiral wrapped coil bundle. It may be a little tight but the wire bundle will slip off. Adding the spacer will take about 15 to 20 minutes. Don't rush! Compress the spiral wrap (sideways) after going under each hook ensuring that it is wound tightly around the coil bundle. If a few of the outer coil wraps are a little loose when finished, just pull the coil between you hands when it is off the coil form and work your way around the coil, pulling hard every few inches. This will seat the Teflon wire inside the spiral wrap. You may need to go around the coil a few times, but the Teflon wire will snug up inside the spiral wrap. If you want to add a second layer of spiral wrap, you can add it with the coil off the "C" hook coil form.

Fast Coil Factors

"An 11" diameter coil is optimum for beach work and is the best compromise between small object sensitivity, depth, pinpointing and coverage" ***Eric Foster***

If you want to make the fastest coil possible in the 10" to 11" diameter range, use Teflon insulated wire with 300uH to 320uH inductance. Teflon insulation makes a coil with less capacitance than a coil with PVC insulation. Teflon has a dielectric constant of about 2, compared to 4 to 6 for PVC. Teflon spiral wrap makes a very good shield spacer but it is very expensive. As an alternative, you can use polyethylene (PE) spiral wrap that has a dielectric constant of about 2.2 and is easily available and inexpensive. When you combine the thinner wire bundle of using AWG 30 wire with two layers of PE spiral wrap you will make a coil that has a low coil-to-shield capacitance. AWG 30 wire has about 0.1 Ohm resistance per foot and makes a 19-turn, 10.5" inside diameter (ID) coil with about 5.4 Ohms resistance. When you combine this resistance with the on-resistance of the MOSFET coil driver, you will have a coil that has a peak current between 1 and 2 amps (Ohms Law). MOSFETS have an on-resistance that can range from 0.2 Ohms to about 5 Ohms. The peak coil current is a function of the coil resistance plus MOSFET on-resistance and any other series resistance. The time constant of the coil (L divided by R) will also govern the peak current in the coil for a given pulse width. Longer TX pulse widths will create a higher coil current and create a higher fly-back pulse. Higher mono coil currents take longer for the fly-back pulse to settle down and results in longer delays.

"On the Hammerhead it would help to reduce the coil current and the gain of the preamp. Both will help in allowing for a faster delay especially when trying to get larger coils to work at less than 10uS." ***Reg Sniff***

Insulation Thickness
For comparison, to help demonstrate the insulation thickness point, I wound an identical 19-turn coil, 10.5" diameter using magnet wire with thin enamel insulation. Here are the coil statistics. Wire inductance on the hook coil form: 309uH, 1.25MHz self-resonance. With a PE spiral wrap added, the coil inductance went up to 384uH with a 733KHz resonance. This higher inductance occurs because the spiral wrap compresses the coil together but the resonant frequency is lower because the insulation is very thin making the coil capacitance higher, 123pF.

Here is how to calculate the capacitance of a coil after you measure your coil's self resonance.

Go to the following web site http://www3.telus.net/chemelec/Calculators/LC-Calculator.htm and enter the coil inductance in micro Henries (uH). Then enter a capacitance estimate of about 100pF. If your estimate shows a resonant frequency answer that is higher than your measured coil resonance, enter a higher capacitance number until the answer matches your measured coil resonant frequency. The magnet wire 384uH coil with a 733KHz resonance has 123pF of capacitance while the Teflon wire insulated coil of 317uH resonates at 1.25MHz and has 51pF of capacitance.

When Shielding Is Needed
Shielding the coil is required for delays below about 30us. The shield does two primary things:

1. It eliminates the coil responding to the ground at low delays when the coil is lowered to the ground and
2. It protects the coil from picking up electrical noise.

At low delays, finding a good shield material can be a challenge as the shield can become a target and can reduce the coil's sensitivity. You can actually experiment with shield material using an existing coil. Just see if the candidate shield material is minimally detected on your PI machine when held close to the coil while operating at the lowest delay setting in the 8us to 15us range. The most accurate test occurs when the candidate shield material is moved near the coil being held by a piece of wood or plastic rather than your hand especially if your coil is not shielded.

Fig. 6 Piece of Scotch 24 shield material held by a wood stick being tested.

Shield Materials
There are a wide variety of materials that can be used effectively as a PI coil shield. One consideration for a shield includes the ability to solder directly to the shield material. If you can't solder to the material, a ground lead must be mechanically fastened to the shield using conductive glue/epoxy or electrical tape securing a bare wire to the shield. Wire carbon-based glue is available in a 0.3oz (9ml) jar from www.andesproducts.com. Another consideration is the minimum delay at which the shield material itself is detected. Here is a list of some good and fair shield material:

- 3M 1190 (good) copper fabric tape, can be soldered
- Scotch 24 (good) wire mesh shielding tape, can be soldered, (used for the coil in this article)
- Conductive Mylar (good), mechanical shield fastening
- Aluminum foil, (fair) only at longer delays, mechanical shield fastening
- Lead tape (good), can be soldered

Fig. 7 Scotch 24 mesh shield being secured to coil with tape over second layer of spiral wrap.

There are two ways to add the shield depending on the size and shape of the shield material used. If you use two layers of spiral wrap, the final wire bundle diameter will be .25" with a circumference of 0.785". This allows you to use a .75" wide 3M 1190 shielding tape applied around the circumference and bent over to almost totally enclose the total coil with a 0.035" gap.

The other method is to hold the tape roll at an angle and spiral wrap around the whole coil wire bundle without overlapping the tape too much. **Be sure to leave a small shield gap where the two wire leads exit the coil.** Practice soldering on a piece of scrap tape first. Use a small piece of flat metal to act as a heat sink under the point where you are soldering to prevent burning a hole in the tape. Attach the wire so it is running in the same direction as the coil circumference. This can be a short piece of stranded wire or a piece of thin de-soldering wick long enough to reach the coax cable. Apply a few wraps of electrical tape over the solder joint to minimize strain on the solder connection. This is one connection that you don't want to come undone after the coil housing is sealed up.

Fig. 8 Scotch 24 mesh shield

Once the whole coil is wrapped (if you are using 3M 1190), cut the tape just before the gap, slip the heat sink under the tape and then solder the ground lead. I used Scotch 24 to shield my coil. I wrapped the 1" wide shield mesh around the outer circumference of the coil, securing it in eight places, then spiral wrapped electrical tape around the coil to tightly secure the shield against the PE spacer. The measured coil-to-shield capacitance of Scotch 24 wrapped around the 10.5" coil is 104.7pF

Shielding Lowers Coil Self-Resonance

It turns out that only about 20% of the 104.7pF coil-to-shield capacitance reduces the with-shield coil resonance to 1.0445 MHz (with shield connected to one coil wire). This is due to the distributed capacitance of the shield over the 19-turn coil separated by two layers of a PE spiral wrap. Distributed capacitance is a very complex calculation. It is best measured with an LC meter once the shield is added to the coil. Just clip one lead of the LC meter to the shield and the other lead to one coil wire and note your capacitance measurement. The coil self resonance with the shield added, represents 72pF of capacitance compared to 54pF capacitance without it, only adding 18pF to lower the coil resonance.

If you are doing these measurements to follow along while making your coil, you will get a small variance in the measured values. When you add the shield to the coil, the inductance of the coil will actually measure about 7 to 15uH higher. When I added the Scotch 24 shielding tape, the inductance went up to 324uH (from 317 uH without the shield). From this point forward, use this new coil inductance (with shield) in all your calculations. Another interesting coil characteristic is that the coil-to-shield capacitance may be different by a few Picofarads when either the start or the end winding is used to make this measurement. This is due to how the wire lays inside the coil bundle relative to the coil winding distance to the shield.

When applying the shield to the coil, ensure that there is a small gap where the two coil wires enter and exit the coil *(repeated for emphasis)*. If there were full shield continuity around the coil, the shield would look like a shorted turn and the sensitivity of the coil would be seriously degraded or may not even work.

Assembly

Mount the coil inside the upper half of the Hayes Electronics coil housing coil shell. Install the waterproof strain relief (supplied by Hays Electronics) and expose just enough coax wire to allow soldering and putting a thin nylon wire tie around the coax inside the coil housing to prevent the coax from pulling out. Pull it tight using pliers. You can epoxy the tail of the wire tie to the coil housing wall for extra coax security. Solder one coil lead to the coil shield and then the coil shield lead to the coax braid. Solder the other coil lead to the coax center conductor. Use heat shrink tubing over the connections to secure the wires.

If you make the coil for use on the beach or for use in the water, the coil needs to be sealed up to be waterproof. Once the coil is made, installed inside the coil housing, tested and sealed up, it is important that the coil be secure inside the coil housing. Any movement of the coil relative to the shield or movement of the coax cable could cause a false signal. A sealed up coil is very difficult to open without damaging the housing so make it right before sealing it up.


Fig. 9 Coax cable secured with wire tie. Epoxy tail of wire tie to coil housing wall.

Shield Material Experiments

There is a web site that allows you to calculate the capacitance of coax cable with different dielectrics. This will be useful for estimating your coil-to-shield capacitance and see the impact of using a variety of spacer material and spacer thicknesses. Go to the following web site, http://www.mogami.com/e/cad/electrical.html and insert your coil bundle diameter in mm as the center conductor. Input the diameter of the shield spacer in mm. Finally select the dielectric and see the equivalent capacitance for a one meter length of coax. Divide the answer by the ratio of your coil circumference compared to one meter. The coil bundle described above using 19 turns of AWG30 Teflon insulated wire is 3mm, and two layers of PE spiral wrap are 6mm. The answer in the on-line calculator is 184pF/meter. Divide 39 inches (one meter) by the coil circumference of 33 inches and you get .8462. Multiply 184 by .8462 to obtain the equivalent capacitance of the coil circumference which is 155.7pF and is close to the actual measured coil-to-shield capacitance. Enter different materials used for a spiral wrap spacer and see that PE is very close to Teflon. Scotch 24 is a wire mesh shield and has less surface area and less capacitance than a solid shield covering the same area. This is why the Scotch 24 measures 104.7pF, 51pF lower than the calculated capacitance noted above. Also, distributed capacitance of a coil is a little different from capacitance of a single conductor coax. This exercise helps you do “what-if” design tradeoffs and experiments using a variety of materials that you might have on-hand.

Securing The Coil

Before sealing up the coil housing, try using the coil so that, if necessary, it can be easily opened, inspected and modified. The easiest way to secure the coil inside the top of the coil shell is to cut pieces of Styrofoam strips to fit inside the top-half of the coil shell wings under coil (with coil upside down). The cleanest cuts are made with a fine-blade scroll saw. First I used two strips 0.5” wide, 0.25” thick by 13” long. Then I used two pieces 3/16 wide, ¼” high by 13” long to wedge around the inside of the coil housing, forcing the coil bundle to the edge of the coil housing. I cut one piece of Styrofoam 2.25” wide and 13” long to fit the center channel. I pressed the coil housing into the center strip to obtain an impression of the outer contour of the housing edge. Using a fine tooth X-acto saw blade, I cut “L” shaped step on each end of this piece of Styrofoam to secure the edges of the coil firmly under the coil as well as press the coil to the edge of the coil housing. This makes a secure coil that can be either sealed up for waterproof use or temporarily assembled to test your new coil creation. Place the bottom piece of the shell on the top piece and seal with electrical tape for temporary use. This is not waterproof but allows you to try out the coil on land or the beach once you solder the coax to the coil leads and shield. The coil without the coaxial cable, but fully assembled with both halves and internal foam weighs 8.3 ounces (0.236kg) and with 33” of coax and connector weighs 10.6 ounces (0.300kg).

Fig. 10 Styrofoam strips ready for coil insertion

The Hayes coil housings come with some scrap pieces of plastic to be added to MEK solvent to make a glue paste to seal up the coil. **Caution: Use this in a well ventilated area.**

The Final Steps

The coaxial cable, connecting the coil to the PI circuit, adds capacitance to the coil and tends to slow down the coil. Coils attached with 7 ft of cable can add about 200pF of capacitance to the coil circuit. Typically, 75 ohm coax has about 16pF per foot while 93 ohm coax has about 13pF per foot.

By using a low output capacitance coil driver MOSFET (below 100pF), Teflon insulated coil wire, a polyethylene shield spacer, properly adjusted damping resistor, and a short coax (about 33 inches) you can squeeze the most speed out of your coil. The value of your damping resistor is an indicator of the total TX circuit capacitance and coil capacitance. Higher values of the damping resistor indicates less capacitance to damp while lower values of damping resistor values indicate a higher capacitance to damp.
http://www.freepatentsonline.com/7075304.pdf

Final Test

The 300 to 350uH coil described here will critically damp somewhere between 750 to 1000 Ohms, depending on the coax cable length and MOSFET being used. The damping resistance should be adjusted experimentally while observing the output of the first amplifier (Hammerhead IC6) with an oscilloscope. Place a 1200 ohm resistor in parallel with a 5K ohm pot that has a 1200 ohm limit resistor in series with the pot. This allows you to adjust the damping resistor value in the range of 600 to 1K ohms, (R11 in the Hammerhead) to optimize the coil’s performance on your PI machine. Once the critical damping is set, measure the combined value of the 1200 ohm resistor and pot (with the series resistor), substitute with a fixed resistor or resistor parallel combination to obtain the same value. If you want to experiment with many coils you can insert a 1200 ohm resistor in R11 and then mount the 5k pot and 1200 ohm limit resistor next to your coil connector where the connection points to the coil at the connector are close.

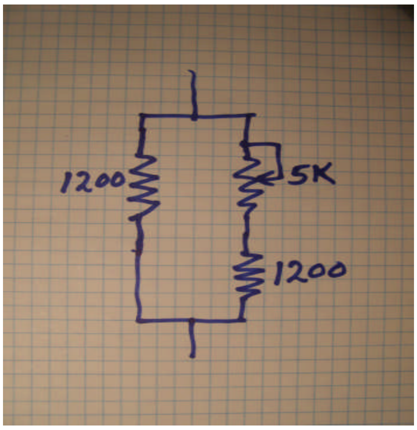

Fig. 11 Damping resistance set-up for adjustment.

“The switch off speed is governed by the damping self resonant frequency of the coil circuit. Critical damping gives the fastest rate, but generally the coil is slightly over-damped” ***Eric Foster***

A Little Tutorial

Coils will suddenly stop responding when the PI circuit delay is adjusted lower than the coil’s natural minimum delay. While waving a U.S. nickel, gold ring or nugget target under the coil, listen for a response while slowly reducing the delay control. If you get to a point where the PI machine suddenly stops responding to the target, you have reached the natural delay for that coil at that delay control setting. One way to speed up the coil is to reduce capacitance somewhere. If the PI machine stops responding very close to the minimum desired delay, you may be able to tweak the damping resistor value slightly to allow the PI machine to operate over its full delay range with your new coil. Some of my own crude measurements indicate that, for each 100pF of capacitance I reduce in the coil or TX circuit above 10uS, I can speed up the coil by about 1uS. This is a good rule of thumb to keep in mind so you can examine where you might want to look to speed things up if possible.

Other Insulation Materials

Coil self resonance, including shield capacitance and the coax cable, is a very comprehensive measurement that tells you much about the potential speed of your new coil. All coils have distributed capacitance between the coil windings that is primarily affected by the wire insulation thickness and insulation material. Thicker insulation holds the coil turns farther apart which reduces the capacitance as reflected by a higher coil self-resonant frequency. Also, thicker wire insulation tends to slightly reduce the coil inductance compared to thinner wire insulation. The wire or spacer insulation material has a dielectric constant. PVC has a dielectric constant range of 4 to 6 while Teflon insulation has a dielectric constant of about 2.

The dielectric constant of any insulation material is an invisible characteristic that has an impact on your coil's self resonance. If we compare two spiral wrap spacers, one with a PVC dielectric constant of 4.4 and another with a Polyethylene (PE) dielectric constant of 2.2, we have a difference between the two materials of 2 (4.4 divided by 2.2). If the coil-to-shield capacitance of the PVC is 140pf then the coil-to-shield capacitance of the same coil using a PE spiral wrap is about half. This same thing occurs when you wind two identical coils using the same wire size and same insulation thickness but each having different type of insulation. If we compare the self resonance of coils with PVC insulation and Teflon insulation, the coil with the Teflon insulated wire has a higher self resonance than the PVC insulated wire. Kynar insulation, the type used on wire-wrap, has a dielectric constant of about 6. A 320uH 10.5" diameter coil made with Kynar insulation (AWG 30, 0.019"OD), 18 turns has a self resonance of about 861KHz while the same size Teflon insulated coil (AWG 30, 0.024"OD) has a 1.25MHz self-resonance. Adding a second layer of ¼" OD PE spiral wrap to the Teflon coil lowers the coil's self resonance by about 11KHz to about 1.239MHz. This is due to the additional PE material being in the coil's electrostatic field. The insulation on the Kynar insulated wire is also a little thinner than the Teflon insulation thickness, and this also contributes to the Kynar insulated wire coil having a lower self resonant frequency.

A good source for PE spiral wrap is www.usplastic.com. I used the following two item numbers to make the coil in this article:

- 41164, Poly-E Spiral Wrap Black ¼" OD 100 ft and
- 41163, Poly-E Spiral Wrap Black 1/8" OD.

US Plastic Corp. has a catalog full of parts that will help coil makers improvise coil parts.

To see the impact of capacitance on your coil's performance, measure the self resonance with the:

1. Coil alone,
2. Coil with just the spiral wrap spacer,
3. Coil with the shield,
4. Coil with shield and the coaxial cable.

What you will see is that the coil alone has the highest self resonant frequency. It will be slightly lower with one layer of spiral wrap spacer, very slightly lower with a second layer of spacer, lower with the shield added, lower when one lead of the coil wire is connected to the shield and finally lower when the coax cable is attached. Then when the coil is connected to the PI TX/RX circuit it will see the TX MOSFET capacitance and the additional loading of the RX input resistor. The same 19-turn coil wrapped with a PVC spiral wrap spacer has a 1.167MHz self resonance while the PE spiral wrap spacer has a 1.25MHz self resonance. This difference is due to the dielectric constant of the spiral wrap material. As a rule of thumb, the final self resonance of a coil, shield spacer, shield and coax should be about half of the coil-alone self resonance. To get a coil to operate at or under 10uS delay, shoot for a self resonance about 40% lower than the coil-alone self resonance. Anything you can do to make the final coil (with shield and coax) self resonance higher will make a coil with less capacitance and one that has the potential to operate at a lower delay.

Before redesigning your coil in an attempt to make it faster, try these three things first.

1. See if you can find a lower output capacitance MOSFET coil driver.
2. Use a lower capacitance coax. This is useful if you must make a coil with a longer coax that you want to operate at the lowest possible delays.
3. Add a resistor of a few ohms in series with your coil. This will reduce the fly-back voltage, lower the coil current and allow you to sample a little faster.

All design is a compromise. Try to understand the variables that you can control and the things that are relatively fixed.

Cable Length Design Consideration

The coax cable is a large capacitance contributor to lowering the coil's self resonance. If we use a RG8X coax with 27pF per foot capacitance, then a coil with 2.75 feet adds 75pF (2.75 times 27) to lower the coils self resonance. Seven feet of coax will add 189pF (7 times 27). The value of the damping resistor is higher with the shorter coax as there is less capacitance. RG8X coax was chosen because the center conductor is stranded and is easily available in marine supply stores. If you are really determined to make a fast coil, use Phillips PXT1000 audio coax cable (solid center conductor) or equivalent at 17pF per foot. Extended flexing of this cable may become an issue if used for a longer hip-mount configuration. This is a good reason why some PI designs mount the control box on the shaft with a short coil coax, and remotely mount the heavier batteries and possibly some final audio amplification in a body-mounted box.

If you make only one coil for your PI machine, set the damping resistor value for that coil on the circuit board. However, if you plan to use multiple coils on your PI machine, place a little higher value damping resistor of about 1000 to 1200 Ohms (0.5 to 1 watt) on the circuit board and then trim the final damping value by adding a ¼ watt resistor between 1000 and 5000 Ohms in the connector housing in parallel with the coil connections. This will allow you to change coils and have optimum damping for each coil. These values must be obtained experimentally by monitoring the output of the first amplifier (IC6 on the Hammerhead) with an oscilloscope while adjusting a variable damping resistor temporarily placed across the coil to achieve critical damping (no ringing).

Coil Self Resonance Measurements

To do basic coil measurements described in this article, you will need a few pieces of test equipment. A signal generator with a 2MHz maximum frequency (preferably with a digital frequency display) is used to stimulate the coil. An oscilloscope is necessary to observe the waveform across the coil as the frequency from the signal generator is swept to find the coil's resonant frequency. A scope probe can load the coil circuit down enough to alter the self resonant measurements by 30 KHz to 100KHz (or more) lower than the actual resonance. One way to minimize this is to use a 10X probe which has lower capacitance than a 1X probe. See the following diagram for a good coil test setup. Note that there is a small value capacitor in series with the scope to minimize loading on the coil. A small capacitor can be made by twisting about 1 inch of wire together to form a "gimmick" capacitor that uses the capacitance between the wires separated by the wire insulation acting as the dielectric.

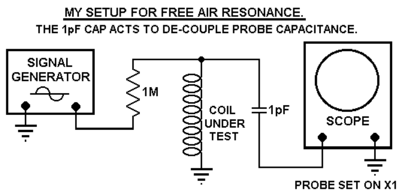

Fig. 12 Coil self resonance test setup.
Courtesy, http://www3.telus.net/chemelec/

Coil Size Considerations

Using the right coil diameter for the size and depth of the targets sought will help to optimize your searching. If a target is just detected at a depth equal to the coil's radius, then the coil size is just right for that particular target size and metallic composition. Going to a larger coil will reduce the detection depth on that target. If the detection depth is more than the coil radius, then you can increase the coil diameter and increase the detecting depth for that particular target.

PI mono coils of varying diameters have different numbers of coil turns. Smaller coils have more turns to achieve the same inductance as a larger coil would have. Smaller coils are more sensitive to near-coil smaller objects because the magnetic field is stronger due to the increased number of coil turns, but the far-field strength is less. Larger diameter coils have fewer turns than a smaller coil but reach deeper for larger targets. Since the identity of most targets is unknown until retrieved, it is better to use a coil size of 10 to 12 inches in diameter that accommodates a wide range of small objects and only go to a specialized coil when your objective is to seek a specific target size, metal composition, and depth, or when the ground conditions dictate a specialized coil. Beach hunters tend to want to cover a lot of ground with each sweep so larger round coils or rectangular coils in the 6" by 18" size range work well in this environment. Nugget hunters seeking very small nuggets in streams or stream beds need smaller coils to fit into tight spots and need the extra sensitivity of a smaller coil with more coil turns to obtain a response from those small nuggets.

The techniques described in this article can be used to make each coil of a double D (DD) coil where there are separate transmit and receive coils. The details for making DD coils require some additional design considerations that will be the basis for a future DD coil design article.

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